

The coastal landforms and peripheral wetlands of the Peel-Harvey estuarine system

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Abstract

Numerous, varied physical (hydrodynamic, sedimentologic and geomorphic) processes interact to determine the type, location, configuration, extent and evolution of the shore and the peripheral wetlands of the Peel-Harvey system. Twelve types of shore are identified in the estuarine system: tidal shoals, active tidal delta, stranded channel shoal complex, relict tidal delta, stranded estuarine embayment, spit-lagoon complexes, beachridge complexes, marginal platforms, erosional sandy shore, limestone cliff—pocket beach shore, lobate fluvial delta complex, and elongate fluvial delta complex. Ten of these shore types wholly or partly contain wetlands.

Introduction

The Peel-Harvey estuarine system has been studied from physical, chemical, biological and geological viewpoints, as summarised by Hodgkin *et al* (1980). This estuarine system is now regarded to be of undoubted regional to national significance because of its natural history features, the wealth of avifauna that utilize the area, and the case study of eutrophication that it presents. Significantly, also, large tracts of estuarine shores have been reserved for flora and fauna in recognition of the role of foreshores in fauna conservation.

Most of the work on the Peel-Harvey estuarine system to date has concentrated on subdivision of the sublittoral zone. For instance, Brown *et al* (1980) subdivide the system (with formal geographic nomenclature) into components of basins, shelves, sills and deltas. However, the shore types of the estuarine system, encompassing the supralittoral and littoral zones, to date have not been extensively described and classified, particularly from the point of view of development of peripheral wetlands. The objective of this paper is to provide such a description: so that the physical basis for development of peripheral wetland habitats and their flora can be appreciated; so that representative but as yet unsecured tracts of shoreline can be highlighted for potential conservation; and so that the information may provide a framework for later more detailed studies. The approach adopted here in subdividing a large estuary into various shore types can be applied to other estuaries in Western Australia and elsewhere in Australia to provide a basis for differentiating types of peripheral wetlands, and for determining whether there is adequate variety of shore and wetland types secured in reserves.

Materials & methods

This study is based on ground surveys to map the terrain and vegetation units, transects through representative areas (Fig. 1), and interpretation of aerial photographs. The entire shoreline of the Peel-Harvey estuary was surveyed and classified either by boat or by land access. Detailed transect surveys involved: topographic levelling relative to AHD; soil sampling; augering and trenching to 1 to 4m to determine stratigraphy; groundwater sampling; and describing floristics and structure of the vegetation. Selected localities also were cored to 30m using a reverse air circulation corer (Fig. 1). The structure, fabric, texture and composition of soil and stratigraphic samples were described in the laboratory to define the lithologic suites.

Regional setting & coastal processes

The geomorphic setting, climate, hydrology, hydrodynamics and sedimentologic processes of the estuarine system are described briefly below as background for this paper. More detailed information on some of these physical features for this area is presented in Hodgkin *et al* (1980), Black & Rosher (1980) and Brown *et al* (1980). The sedimentological processes operating in the Peel-Harvey system are largely undescribed in the literature.

Geomorphic setting

The Peel-Harvey estuary is a compound type barred by a Pleistocene barrier, and essentially is three coalesced estuary systems; its connexion with the sea is mostly choked by an emergent (stranded) tidal delta and channel

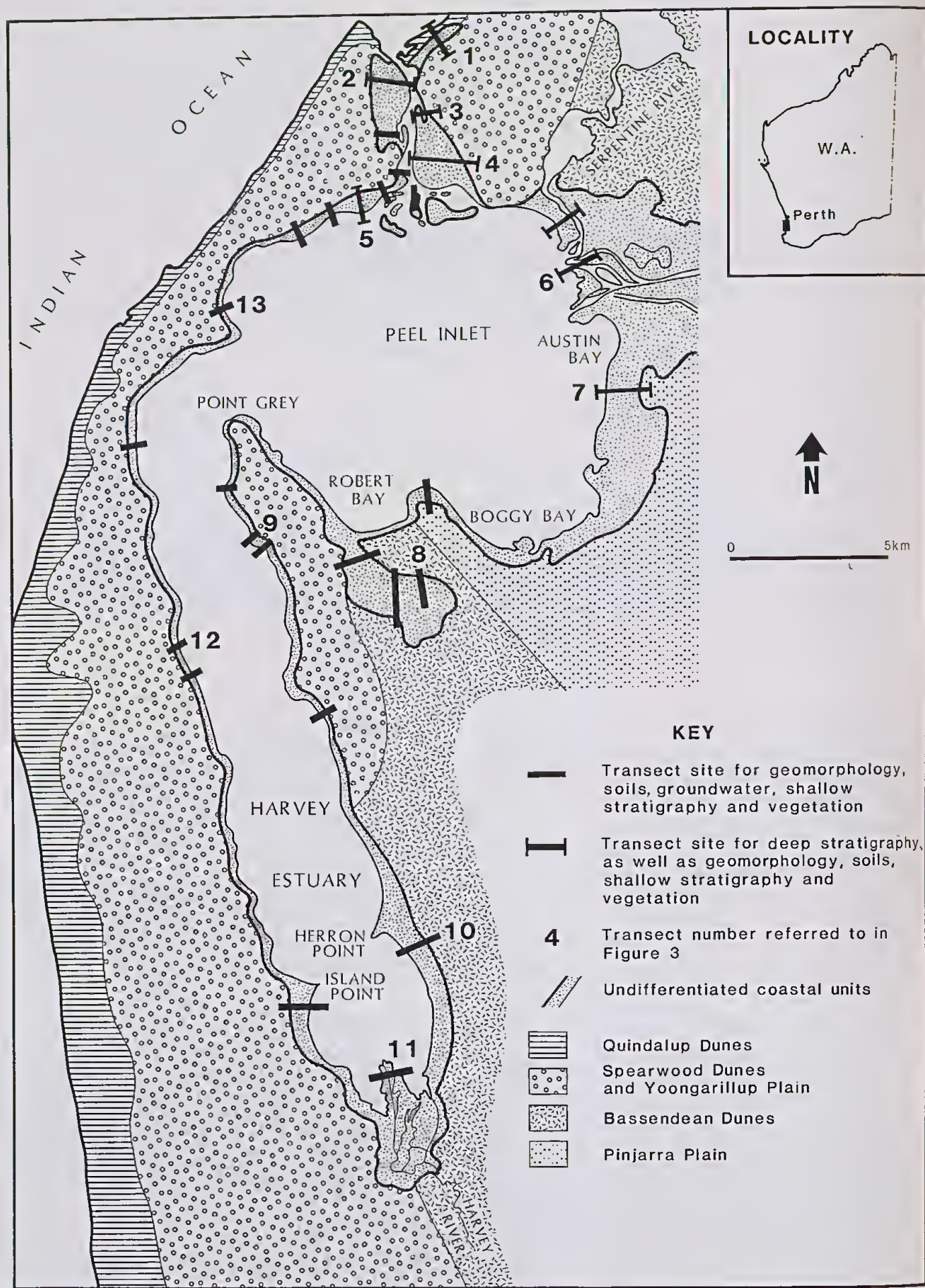


Figure 1 Locality map showing the Peel-Harvey estuary system within the framework of the major geomorphic units in the region (simplified after McArthur & Bettenay 1960), and location of the sampling transects of this study.

shoal complex. Overall, it is a difficult estuary to classify because it is complex. For instance, it is not easily classified using the scheme of Pritchard (1967) because its external form is due to marine inundation of three juxtaposed Pleistocene landforms that have been incised by three rivers.

The Peel-Harvey estuarine system has been described at the regional scale by Brown *et al* (1980) and Hodgkin *et al* (1980). The entire system is the estuarine confluence of three separate rivers, and is composed of 1) the circular Peel Inlet (the receiving basin for the Murray and Serpentine rivers), 2) the elongate Harvey estuary (the receiving basin for the Harvey River), and 3) the narrow linear exchange channel (which connects the estuary with the ocean). The main regional geomorphic components framing the system are (Fig. 1): a barrier ridge of Spearwood Dunes to the west; aeolian and fluvial lowlands of Bassendean Dunes and Pinjarra Plain to the east; and riverine discharge points (McArthur & Bettenay 1960). These units have an influence on the development of coastal landforms and sediments along the estuary shore. The wetlands within the Peel-Harvey system have been considered as a consanguineous group, and have been termed the Peel-Harvey Suite by Semeniuk (1988).

Climate

The climate of the area is subtropical, with hot dry summers and wet mild winters (Gentilli 1972). The important features for this study are rainfall, evaporation and wind. Rainfall is moderate, c 825 mm/yr, falling mainly in May to October (Bureau of Meteorology 1975); it recharges onshore groundwater reservoirs, provides runoff and groundwater discharge, waterlogs the estuarine peripheral flats, and seasonally dilutes the saline estuarine waters. Evaporation is high, c 1980 mm/yr; it has a major effect on the open waters and peripheral wetlands, because of the large surface area and relative shallowness of the estuary, and causes local hypersalinity in summer.

Wind generates wind waves, currents, littoral sediment drifts, and aeolian drifts. There are three wind systems that affect the region: cyclone-anticyclone winds, the landbreeze-seabreeze system, and storms (Gentilli 1972, Steedman & Craig 1983). During summer, with the anticyclone belt located to the south of the continent, winds in the region derive from E sectors, and landbreezes and seabreezes result in moderate winds from E sectors in the morning, and strong SW winds in the afternoon. In winter, with the belt to the north, winds derive from S to NW sectors. In winter there also are periodic storms deriving from SW to NW, but mainly from NW.

Hydrology

The estuarine system is a receiving basin for meteoric, fluvial, marine and ground waters, and peripheral wetlands of the area are maintained by one or more of these hydrological sources. Rainfall accounts for 20% to 30% of the fresh water input, while rivers and groundwater discharge account for the rest (Black & Rosher 1980). The rate of input and exchange of marine water is variable, depending on atmospheric conditions, rate of freshwater flow, and salinity of estuarine water. The estuarine waters fluctuate seasonally from brackish (mixed riverine and residual saline water from a previous season), to oceanic (when tidal exchange and wind mixing combine to flush

the system of fresh water), to locally hypersaline (when summer evaporation and limited exchange cause elevation of salinity particularly at the head of Harvey Estuary). The uplands bordering the estuary are underlain by fresh groundwater. The contact of estuarine water and fresh groundwater is an inclined interface. Groundwater systems of the uplands function separately to the estuarine water body, although the water table in proximity to the estuary shows evidence of movements aligned to tidal fluctuations.

Hydrodynamics

The Peel-Harvey estuary is dominated by 5 main hydrodynamic processes: wind wave action; wind-induced current action; oceanic wave action; tidal exchange; and fluvial discharge. Wind waves and currents form within the estuary under the prevailing wind and storm conditions. The waves emanate from variable directions and are of variable wave length dependent on fetch. Because of the large fetch across Peel Inlet, winds from all directions are important in developing wind waves significant for shore processes. In contrast, the Harvey Estuary is influenced mainly by wind from SW and NW sectors. Oceanic wave action is located only within the exchange channel area and has components of wind waves and diffracted swell which have propagated through the exchange channel. The estuary is microtidal (Hodgkin & Di Lollo 1958, Easton 1970), and tidal exchange results in flood and ebb currents and water mixing, particularly within the exchange channel; these tidal currents, together with those induced by wind, are significant in transporting and accumulating sediment. Fluvial discharge results in influx of freshwater, generation of currents, transport of sediments, and mixing and flow into the ocean. The fluvial discharge is significant since it amounts to five times the volume of the estuary in a little over 4 months (Black & Rosher 1980).

Sedimentological Processes

The geomorphology of the shoreline and peripheral wetlands of the Peel-Harvey system are mainly the product of macroscopic sedimentologic processes, and these are briefly described as background to understanding the types and evolution of the shore. Smaller scale processes, such as bioturbation and current rippling, are not considered here as they merely modify sediments emplaced or shaped by the macroscopic processes. The sediments within the Peel-Harvey estuary have been derived from 5 sources (Brown *et al* 1980), viz fluvial, marine, internally reworked sediments, aeolian, and autochthonous biogenic sources. These result in sediments being composed of siliciclastic grains, clay minerals, skeletal components and organic detritus.

Numerous, varied, physical sedimentologic processes determine the location, configuration, extent, type and evolution of shore types and peripheral wetlands of the Peel-Harvey system, but they can be described under 3 main groups: estuarine; fluvial; and marine. Each dominates a geographic area and involves some mechanisms specific to that area.

Estuarine The estuarine sedimentological processes: wind-wave action, longshore drift, sediment transport and accumulation, and shoreward aeolian transport.

Wind waves erode, rework, resuspend and transport sediment in all environments. The major sites of accumulation by wind waves are the shorelines, where beachridges are formed, but additional constructional and destructional features resulting from wave action include shoal and spit accumulations, small cliffs and channels. Sediment eroded from shores may be transported offshore to accumulate on shelves and in basins. Mud, for instance, is transported in suspension throughout the estuary where, locally under relatively more quiescent conditions, such as basins, or lagoons behind emergent spits, it accumulates. The sedimentary shelves and the shallowness of the estuarine basins both act to dissipate wave energy, so that wave-developed landforms ultimately are best developed in areas facing long fetches. Longshore drift induced by wind waves and currents transports sediment reworked by waves. These currents build and shape the shoals at numerous sites along the shores of the estuary. Waves may be refracted around points and cusped shorelines, resulting in extensive sediment accumulations, such as Point Grey and Island Point. Waves also contribute to the destruction of fluvial features of deltas. Wind transports any shoreline sediment further onshore to supplement the beachridge accumulations.

Fluvial Fluvial processes result in delta building in the estuarine basins. Lateral deltaic plains have formed by channel switching and crevasse splays. The prograding deltaic sediments coalesce with tidal deposits, while their shorelines are reworked into beaches, shoals and spits. The form of each of the 3 deltas (Fisher *et al* 1969) in this region reflects their hydrodynamic setting. The Harvey River delta is a high-constructive, elongate, fluvial-dominated delta. The Murray and Serpentine river deltas are coalesced, and because they front a large fetch across Peel Inlet, a high-constructive, lobate, more wave-dominated delta is formed.

Marine Marine processes extend into the estuary to influence sedimentation at the channel mouth and within the channel. The main factors induced by marine processes are: oceanic swell, wind and storm waves, longshore drift, and tidal currents. Oceanic swell and wind waves impinge on the channel mouth and translate along the channel length. These build sand bars, swash bars and shoals across the mouth on the ocean side, secondly, in conjunction with currents, transport sediment various distances along the channel, and thirdly, develop distinct sediment geometry along the exchange channel. Storm waves erode, transport and disperse sediment from the channel exit and also may erode, transport and disperse sediments from the marginal shoals within the channel. Longshore drift induced by waves at the oceanic mouth of the channel mostly transports sediment northwards along the coast such that there is no development of an ebb tidal delta. Ebb and flood tide currents within the channel transport marine sediment towards the estuarine basin where it accumulates in tidal-delta shoals and islands. These currents also shape the sedimentary bodies along the shorelines within the channel to form elongate, current-oriented shoals.

Criteria for recognizing shore types

The various shore types along the Peel-Harvey system are recognized and separated on criteria of: the shore terrain being in close (vertical) proximity to the prevailing

estuarine water level and estuarine storm water level; geometry of shore; slope of shore; stratigraphy (geometry and lithologic suite); and similarity of formative processes (such as spit accretion processes versus beachridge accretion processes versus tidal delta accretion, *etc*). Since all the terrain is low lying, small scale features with relief less than 1 m become significant in comparing shore types, or deducing processes, or inferring history. It also is necessary in this type of study, where related shore types are grouped, to ensure firstly that they can be related to present or past Holocene estuarine processes, and secondly that a suite of shore types are linked in terms of common processes and origin. Consequently, some landform groupings in this paper differ from previous studies. Landform groups and boundaries along the north shore of Peel Inlet in this paper, for instance, differ from Brown *et al* (1980) both in the position of the boundary of the margin of the tidal delta and the exclusion of a spit-and-lagoon system from the tidal delta complex, because each has formed in a separate type of environment by different types of processes. The spit and lagoon complexes have formed mainly by eastward littoral drift; the tidal delta shoals have formed by flood tide sediment transport. Similarly, the inland extent of stranded estuarine lowlands in this paper differs from Brown *et al* (1980). The area of "estuarine lowland" along the east of Peel Inlet in figure 3 of Brown *et al* (1980), on the basis of morphology and stratigraphy is the southern part of the flood plain of the Murray River. The landforms developed by estuarine processes, in contrast, are clearly peripheral to the estuary, or to stranded former embayments of the estuary, and are comprised of *shore-parallel* ridges, underlain by a distinct suite of sediments. Thus the criteria used here to determine whether coastal landforms of the Peel-Harvey system are estuarine, and form an inter-related estuarine suite, are that they show a "grain" or orientation in harmony with the estuary coast and with present processes, or are in concordant orientation with former embayments.

The shore types and peripheral wetlands of the Peel-Harvey estuary

The shores of the Peel-Harvey estuary are variable, dependent on the following interactive factors: hinterland type; sediment supply; dominance of estuarine *vs* fluvial *vs* marine processes, sealevel history, and geomorphic degradation. The peripheral wetlands are defined to be those portions of the estuarine coastal landforms that are permanently or seasonally inundated or waterlogged. The wetlands are sometimes well defined, as in the tidal delta and fluvial deltas, and locally more difficult to define because they coalesce with low lying hinterland terrain, or grade into ridge systems no longer influenced by estuarine processes. In the terminology of Semeniuk (1987), the wetlands are mainly basin types, but there are also flats and channels.

Many shore types and their associated wetlands encompass modern Holocene landforms, stranded (fossil) Holocene landforms, and Pleistocene landforms and sediments. Each shore type, and associated wetland, is a result of specific mechanisms of physical processes, sedimentary processes resulting in specific sediment types and geometry, water maintenance and hence water type, and longevity of inundation and waterlogging.

There are 12 types of estuarine shore, and they are listed in order of overall decreasing marine influence: 1) tidal shoals; 2) active tidal delta; 3) stranded channel shoal complex; 4) relict tidal delta; 5) stranded estuarine embayment; 6) spit-lagoon complexes; 7) beachridge complexes; 8) marginal platforms; 9) erosional sandy shore; 10) limestone cliff—pocket beach shore; 11) lobate fluvial delta complex; and 12) elongate fluvial delta complex. Artificial shores are not classified in this paper.

Ten of these shore types wholly or partly contain wetlands. The two that do not contain wetlands are the erosional sandy shore and the limestone cliff—pocket beach shore. Three of the shore types, viz the marginal platforms, beachridge complexes and spit-lagoon complexes are inter-gradational, and form an inter-gradational spectrum (or sequence). Each of the shore types are described below with regard to morphology, sedimentology, groundwater, vegetation and origin, and summarized in Table 1. The distribution of the shore types is shown in Fig. 2. Profiles and stratigraphy of the shores are illustrated in Fig. 3. Radiocarbon ages of the Holocene units and sealevel history of the area are presented and discussed in Semeniuk & Semeniuk (1990).

1 Tidal shoals The tidal shoals, situated in the tidal channel, are wholly wetland complexes. They are elongate, linear bodies, c 300 m long and 80 m wide, attached to the shore at their southern end. The shoals have developed as secondary features on the relict tidal delta and on the cusate projections of the sandy hinterland. The shoals are aligned with the channel by tidal currents, and they protect shallower recessed bays which gradually have accumulated muddy sediment. The shoals have flat tops exposed at low tide; their margins gently slope to depths >1 m. The shoals are underlain by fine and medium sand, and locally, muddy sand. The vegetation colonising the tidal shoals consists predominantly of saltmarsh species of *Halosarcia halocnemoides*, *H. bidens*, *Suaeda australis*, *Frankenia pauciflora*, and *Muellerolimon salicorniaceum*. *Casuarina obesa* has established on the higher ground, forming bands and patches of low woodland.

2 Active tidal delta The active tidal delta also is wholly a wetland complex. It located at the southern end of the exchange channel and is a fan-shaped mosaic of emergent to subaqueous, dynamic shoals. These shoals are rounded to ovoid, ranging in size from 45 m to 600 m in diameter, and separated by distributary channels which scour through the subaqueous sand.

The edges of emergent shoals are eroded; there is a small cliff (15 cm high) with an accompanying perched sand ribbon. When accretion follows, the small cliff is often still evident as a stranded feature. The active tidal delta is underlain mainly by sand and shelly sand, and the emergent shoals are capped by a veneer of mud; the cliff edge of the emergent shoals is overlain by a thin ribbon of sand. The vegetation on the tidal delta is saltmarsh, similar to the tidal shoals. Saltmarsh gives way upslope to shrublands of *Melaleuca cuticularis* or woodland of *C. obesa*.

3 Stranded channel shoal complex. A stranded, or emergent, channel shoal complex, c 2.5 km x 1.0 km in size, occurs along the NW margin of the modern exchange channel. The surface of the landform is undulating, comprised of

a series of very low relief (0.5–1.0 m) but wide, sand ridges and ellipsoidal sand hummocks (former sand waves and shoals), elongated sub-parallel to the former exchange channel margin, separated by low sinuosity shallow linear depressions and channels. At shallow depths the stratigraphy of the stranded channel shoal complex is relatively consistent: the landform is underlain mainly by shelly sand similar to modern estuarine sand shoal and sand flat facies, and represents a littoral to shallow sublittoral surface formed at a higher sealevel earlier in the Holocene; depressions in the landform, lying approximately at high water level, are filled by sand and mud sheets. Some of these depressions are seasonally inundated wetlands, while others are only seasonally waterlogged. At depths greater than 8 m, the stratigraphy consists of channel-fill deposits, with cut-and-fill structures.

The sand ridges and depressions of the stranded channel shoal complex, in their natural state, support *Eucalyptus gomphiocephala* woodland, and assemblages of saltmarsh and shrublands and forests of *M. cuticularis*, respectively. However, much of the terrain has been cleared or developed into canal estates.

4 Relict tidal delta A relict tidal delta, c 1.5 km x 1.0 km in size, occurs along the SE sector of the modern exchange channel. The relict tidal delta largely is an emergent strandplain complex, formed at a higher sealevel earlier in the Holocene. The complex is composed of a flat terrain with relict (abandoned, infilled) tidal channels, and emergent shoals, overlapped by accreted sand and mud sheets which fill depressions lying approximately at high water level. Some of these depressions are seasonally inundated wetlands, while others are only seasonally waterlogged. The relict shoals may exhibit geomorphic patterns such as stranded sand ribbons and former erosional scars, illustrating their accretional history from smaller nucleus shoals. These patterns of accretion and erosion overall are sub-parallel to the margin of the active tidal delta. The stratigraphy of the relict tidal delta is variable over short distances, with lensoid veneers of sand and mud disconformably overlying shelly muddy sand, coarse quartz sand, or medium quartz sand, which in turn disconformably overlies limestone (that has an irregular surface and hence occurs at variable depth). The complex stratigraphy reflects the origin of the terrain that formed by accreting shoals, shifting channels, and filling of channels.

The variable substrates and depth related habitats of the relict tidal delta, in their natural state, support saltmarsh, shrublands of *M. cuticularis*, woodland of *Melaleuca raphiophylla* and *C. obesa*. However, much of this relict landform also has been cleared, infilled or developed into canal estates.

5 Stranded estuarine embayment Stranded estuarine embayments occur to the NE of the exchange channel and to the south of Peel Inlet. The first stranded embayment adjoins the exchange channel, and comprises an elongate estuarine lowland formed behind a barrier dune. At present the lowland is a series of wetlands underlain by tidal estuarine deposits, but was formerly connected to the exchange channel (see Fig. 12 B,C of Searle *et al* 1988). Apart from some isolated stands of *M. raphiophylla* and *Acacia* spp, no natural vegetation remains on this landform.

Table 1
Description of shore landforms of the Peel-Harvey estuary

Unit	Main features	Stratigraphy	Main formative Processes	Main sediment-ologic Processes	Wetland Type	Groundwater ¹ Characteristics	Vegetation
1 Tidal shoals	Microscale inter-tidal & subaqueous shoals aligned with exchange channel	Root structured & bioturbated mud, muddy sand & shelly sand	Tidal currents wind waves	Sediment transport by ebb & flow currents; trapping by vegetation	Estuarine tidal flat	Poikilohaline: Mesosaline	C. obesa woodland; saltmarsh of <i>H. halocnemoides</i> , <i>H. bidens</i> , <i>F. pauciflora</i> , <i>S. australis</i> , <i>S. quinqueflora</i>
2 Active tidal delta	Microscale tidal & subaqueous shoals & channels	Sand & shelly sand capped by a veneer of mud.	Energy loss of tidal currents due to enlarged receiving basin	Deposition by tidal currents; intermittent erosion by storms or heavy river discharge	Estuarine tidal flat	Poikilohaline: Mesosaline to hypersaline	C. obesa woodland; saltmarsh of <i>H. halocnemoides</i> , <i>H. bidens</i> , <i>S. quinqueflora</i>
3 Stranded channel shoals	Undulating terrain of sand ridges & hummocks, with intervening shallow depressions	Sand & shelly sand with mud veneers	Shoals & channels formed at a higher sealevel	Relict, stranded system	Linear basins, flats, shallow channels	Poikilohaline: Mesosaline to hypersaline	Ridges: <i>E. gomphocephala</i> woodland; Depressions: <i>M. cuticularis</i> scrub & closed low forest; saltmarsh with <i>H. bidens</i> ; otherwise mostly cleared
4 Relict tidal delta	Strandplain complex of flats, very low shoals & depressions	Veneers of sand & mud overlying channel-fills of sand/shelly sand, & shoal sand, over-lying limestone	Shoals & channels formed at a higher sealevel	Relict, stranded system	Flats & shallow basins	Varies from hyposaline to mesosaline	C. obesa woodland; saltmarsh of <i>H. halocnemoides</i> , <i>H. bidens</i>
5 Stranded estuarine embayment	Mesoscale basins, locally ringed by low beachridges	Estuarine mud or shelly mud, over-lying sand	Filling by estuarine sedimentation during higher sealevel	Relict, stranded system	Basins	Poikilohaline: fresh/subhaline to hypersaline	Zoned assemblages of <i>M. uncinata</i> , <i>Acacia</i> spp., <i>M. hamulosa</i> , <i>H. spp.</i>
6 Spit-lagoon complex	Mesoscale complex of emergent spits & inter-ridge lagoons	Mud overlying quartz sand in the lagoons. Muddy sand overlying quartz sand in depressions.	Waves, longshore currents	Shoreward transport by waves; longshore movement by currents in northerly direction	Linear basins	Poikilohaline: varies from fresh to hypersaline	Spits: <i>E. gomphocephala</i> woodland, <i>J. furcellata</i> scrub, <i>Acacia</i> scrub; Spit margins: <i>M. rhaphiophylla</i> forest & <i>E. rudis</i> woodland; Depressions: <i>R. inops</i> scrub, <i>M. leptoclada</i> scrub, <i>M. hamulosa</i> scrub/heath, <i>M. cuticularis</i> low forest, <i>M. rhaphiophylla</i> scrub, <i>M. uncinata</i> scrub, <i>J. kraussii</i> sedgeland, <i>Sarcocornia-Halosarcia</i> saltmarsh

Table 1—continued
Description of shore landforms of the Peel-Harvey estuary

Unit	Main features	Stratigraphy	Main formative Processes	Main sedimentologic Processes	Wetland Type	Groundwater ¹ Characteristics	Vegetation
7 Beach-ridge complex	Shore parallel microscale ridges	Quartz sand overlying buried muddy sand or sand	Waves, wind.	Waves accrete sediment into shoreline ridges which are later capped by acolian sediments	Linear basins	Fresh inland, mesosaline near the estuary.	Ridges: <i>R. inops</i> closed scrub, Depressions: <i>C. obesa</i> woodland, <i>M. rhaphiophylla</i> scrub, <i>M. cuticularis</i> scrub, <i>M. leptoclada</i> heath, <i>J. kraussii</i> sedgeland, <i>Halosarcia</i> saltmarsh
8 Marginal platform	Shore parallel microscale bench	Mud & muddy sand overlying sand	Waves, tidal sedimentation	Waves build up sediment against limestone cliffs	Flats & very shallow basins	Poikilohaline: subhaline to hypersaline	<i>M. rhaphiophylla</i> low forest, <i>M. cuticularis</i> low forest, <i>J. maritimus</i> sedgeland
9 Erosional sandy shore	Microscale cliff & narrow shore	Fine, medium & coarse quartz sand	Erosion & alongshore transport by waves & currents	Longshore currents, & wave erosion	none	Subhaline to hyposaline	<i>E. calophylla</i> woodland, with u/s <i>J. furcellata</i> & <i>K. ericifolia</i> ; narrow fringe of <i>J. kraussii</i> sedgeland, <i>S. australis</i> herbland & shrubland of <i>M. rhaphiophylla</i> , <i>M. cuticularis</i> , <i>M. hamulosa</i>
10 Limestone cliff pocket beach	Limestone cliffs & pavement with local overlying sand on estuarine floor; intervening narrow microscale steep pocket beaches	Sand veneer overlying limestone	Erosion by shoreline currents & wind waves	Erosion of sand & limestone by currents, waves, & solution	None	Same as estuary: poikilohaline	<i>C. obesa</i> woodland; sandy shore colonized by <i>J. kraussii</i> sedgeland, <i>S. australis</i> herbland, <i>M. cuticularis</i> shrubland
11 Lobate fluvial delta complex	Macroscale lobate delta: distributary channels, levees, lakes, flats, basins, mid-channel islands, ridges	Mud overlying quartz sand in depressions, quartz sand on ridges	Deltaic processes; estuarine processes; reworking by waves & currents	Deltaic sedimentation; wave reworking of sediment	Channels, basins flats	Poikilohaline: subhaline to hypersaline	<i>C. obesa</i> forest, saltmarsh of <i>H. halocnemoides</i> , <i>H. bidens</i> , <i>S. quinqueflora</i>
12 Elongate fluvial delta	Macroscale elongate delta: distributary channels, levees, flats; broad deltaic plain	Mud overlying sand, or mud overlying muddy sand	Deltaic processes; estuarine processes; reworking by waves & currents	Deltaic sedimentation; wave reworking of sediment	channels, basins flats	Poikilohaline: hyposaline to hypersaline, & brine	<i>M. rhaphiophylla</i> low forest, <i>M. cuticularis</i> low forest, <i>C. obesa</i> low forest, <i>M. uncinata</i> shrubland, <i>M. hamulosa</i> shrubland, <i>Halosarcia-Suaeda</i> herbland, <i>J. kraussii</i> sedgeland

¹ Water characteristics vary spatially and temporally. Salinity terms (after Hammer, 1986) are as follows: fresh—0–1 000 ppm TDS, subhaline—1 000–3 000 ppm TDS, hyposaline—3 000–20 000 ppm TDS, mesohaline—20 000–50 000 ppm TDS, hypersaline—50 000–80 000 ppm TDS, brine—>80 000 ppm TDS.

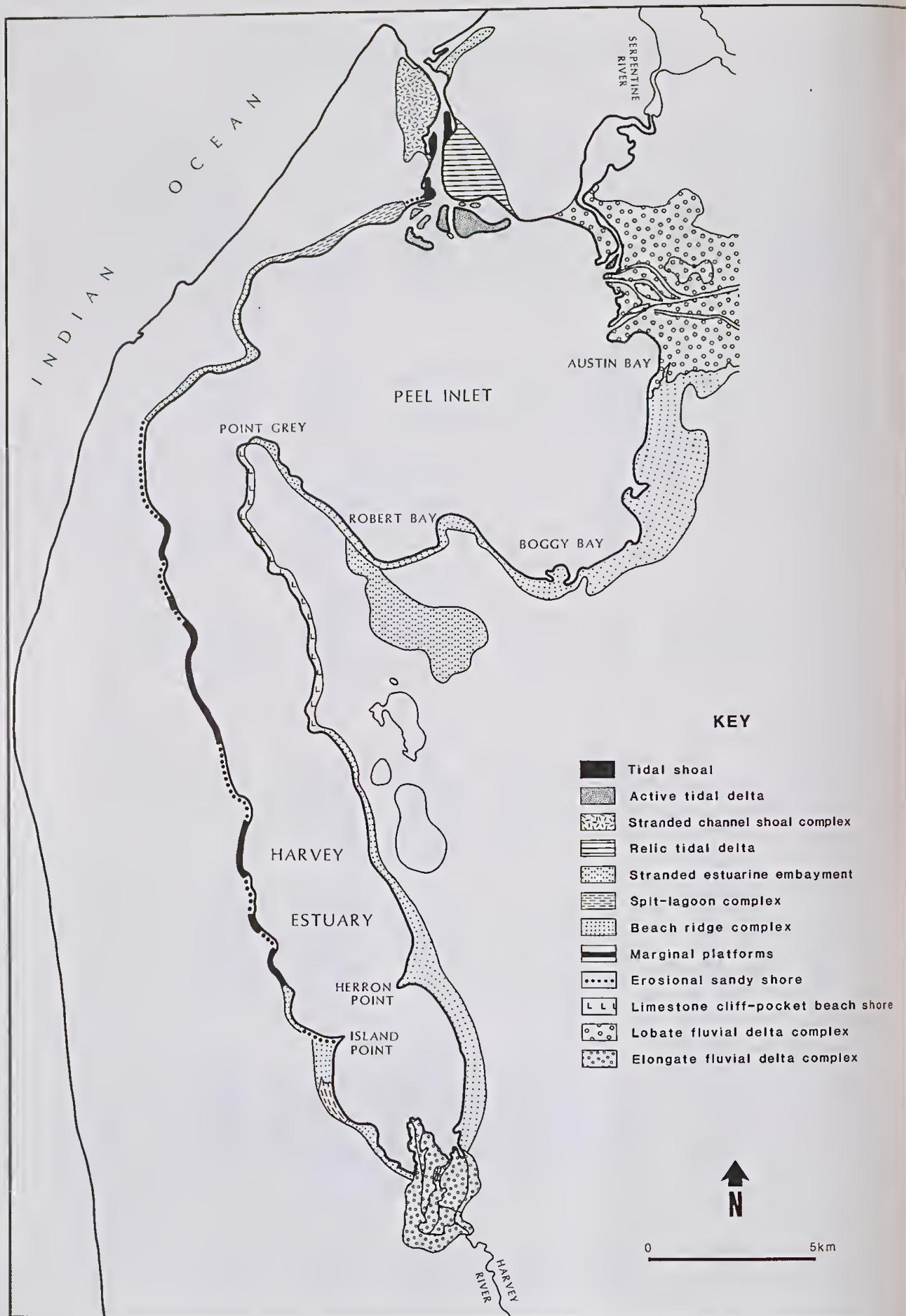


Figure 2 Distribution of the shore types along the Peel-Harvey estuary system.

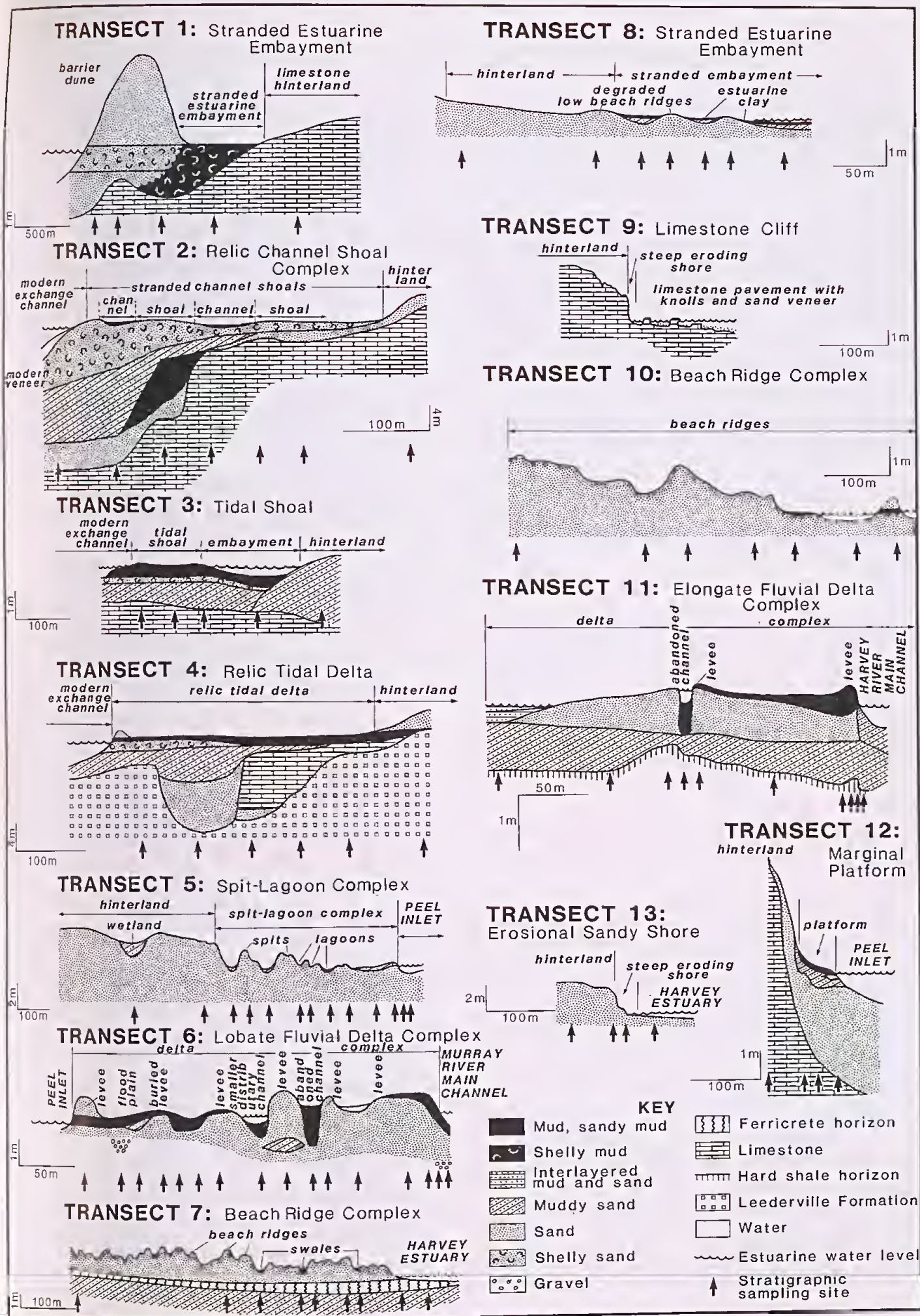


Figure 3 Stratigraphic profiles across each of the main shore types in the Peel-Harvey estuarine system. Location of the transects is shown on Figure 1.

The second stranded embayment is large elongate lowland (wetland) that was formerly a shallow estuarine embayment connected to Peel Inlet by a narrow-necked entrance. The former embayment was developed by estuarine flooding of a wetland basin that was the northern extension of a chain of sumplands comprising the Bibra consanguineous suite in this area (Semeniuk 1988). The margins of the lowland are ringed by a concentric series of low, degraded beachridges. The stratigraphy of the system consists of thin veneer of estuarine clay overlying quartz sand both in the main embayment and in the linear depressions between the beachridges; the beachridges are underlain by quartz sand. Vegetation on the terrain consists of zoned assemblages of *Melaleuca uncinata* on the higher ground, grading to *M. hamulosa* and *H. bidens* in the wetter areas.

6 Spit-lagoon complex The spit-lagoon complex is composed of a series of overlapping to adjacent, emergent, shore-parallel to recurved, narrow spits, built by waves and longshore currents, that enclose elongate to elliptical lagoonal (wetland) depressions. The spit-lagoon complexes occur along the NW shore of Peel Inlet and the SW shore of Harvey Estuary. The complexes are best developed and at different stages of development in the NW of Peel Inlet, where up to 5 main spits can be differentiated. Each spit and lagoon complex is c 1 km long by 300 m wide. The spits are c 70-100 cm high, c 30 m wide, and spaced between 20-100 m apart. The youngest spit occurs at the outer edge of the complex, and the interior of the system is a series of progressively older spit ridges dividing the area into elongate basins or depressions. The spits emanate from the same locus to the west, and extend in a NE to E direction; they overlap part of their length, but terminate at different places. Some spits bifurcate or recurve inwards for short distances along their length. The sediments underlying the spit-lagoon complexes are fine/medium quartz sand with lenses of mud veneering the surface of depressions. The wetland depressions between the spits vary from permanently to seasonally inundated, and both estuarine and groundwater sources maintain them. Ponding of meteoric water or estuarine flood water becomes significant where there are buried mud lenses.

Spit-lagoon areas are colonized by a complex variety of vegetation assemblages which are related to substrate, water table level, topographic height and salinity. The assemblages found associated with the spits are 1) sedge of *Isolepis nodosa* and *Juncus kraussii*; 2) closed scrub of *Jacksonia furcellata*—*Acacia* sp.—*Regelia inops*; and 3) woodland of *Eucalyptus rudis* with understorey of *J. furcellata*. The margins of depressions are colonized by one to several peripheral bands of vegetation such as 1) scrub of *M. raphiophylla* and *M. uncinata*; 2) scrub of *M. raphiophylla*; or 3) closed heath of *Regelia inops* and *M. leptoclada*. The centres of the depressions are vegetated by 1) saltmarsh (*Sarcocornia* sp., *Suaeda australis*, *Halosarcia halocnemoides* and *H. bidens*); 2) scrub of *M. cuticularis*; or 3) low closed forest of *M. raphiophylla* with an understorey of *M. hamulosa* and *M. leptoclada*.

7 Beach ridge complexes Beach ridge complexes occur on the E shore of Peel Inlet south of the Murray delta (Austin Bay area), on the W shore of Peel Inlet, on the E and W shore of Harvey Estuary (Herron Point area and south of Island Point, respectively), and as a stranded ribbon

feature, overlapped by deltaic deposits, to the SE of the Harvey River delta. Beach ridges are ribbon-shaped and extensive along the shore. They are usually 300-400 m wide, but in some areas up to 600 m wide. They are comprised of sand ridges c 50-70 cm (to 1 m) high, and spaced 10-20 m apart with intervening (wetland) swales. The continuous nature of parallel ridges often is disrupted by one of three patterns: 1) discontinuous but still aligned ridges; 2) segments of parallel ridges separated by lagoons, shallow basins, or flats; and 3) short segments of parallel ridges in different orientations coalescing or merging with the main set. These patterns result from earlier cycles of reworking and redistribution of beach ridges by waves, and modification of beachridge orientation by sediment discharge from runoff channels. The landward margin of beach ridges grades into uplands, while the estuary margin usually is reworked into disconnected spits and shoals within the estuary. Locally, the estuary margin is irregular, and may include coastal indentations, small cusped forelands, scalloped shores and projections.

The stratigraphy of the ridges in the Austin Bay area consists of 1-2 m of aeolian, medium sized quartz sand overlying muddy sand or sandy mud, which overlies sand at depths of 13 m. The stratigraphy of the ridges in the Herron Point area consists of 1-2 m of aeolian, medium sized quartz sand overlying medium and coarse quartz sand to depths of 6 m. Along the west shore of Harvey Estuary south of Island Point, the shallow stratigraphy is more complex, with surface and buried lenses of mud interspersed with sand spit/ridge deposits. All ridges in the various areas have been further eroded by wind and sheet wash so that swales are infilled by sand to varying degrees, and capped by humic or peaty soil. Adjacent to the estuary there are occasional veneers of mud in locally broad inter-ridge depressions and lagoons.

The wetlands in the beachridge complexes are inter-ridge depressions which rise to progressively higher levels above the estuary further from the shore. The water table lies c 50-100 cm below the surface of the wetlands, but rises to within 20 cm of the surface under the near-estuary depressions. The wetlands are maintained by minor tidal inundation, or seasonal groundwater inundation, or seasonal waterlogging. The sand ridges are colonized by 1) closed heath or closed scrub of *Acacia* spp, *R. inops*, *J. furcellata*; 2) closed heath of *Homalospermum*; 3) scrub of *Kunzea cricifolia*; 4) low open woodland of *Melaleuca preissiana* and/or *C. obesa* with an understorey composed of elements from 1), 2) and 3) above. The swales are colonized by 1) saltmarsh (*Halosarcia* spp and *Suaeda australis*); 2) sedgeland of *J. kraussii*; 3) closed heath of *Actinostrobilus pyramidalis*; 4) closed heath of *Melaleuca incana*; 5) low closed heath of *M. leptoclada*; 6) low closed heath of *Homalospermum* and *R. inops*; 7) patchy scrubland of *M. cuticularis*; and 8) low closed forest of mixed *C. obesa*, *M. raphiophylla*, *M. cuticularis* and *M. hamulosa*.

8 Marginal platforms Marginal platforms are narrow wetlands located on the western shore of Harvey Estuary between the limestone ridge of the barrier and the subaqueous shelf of the estuary. They are narrow linear platforms, or benches, c 25-90 cm above the water level of the estuary, with widths ranging from 25 m around headlands to 100 m within small bays. The contact of platforms with the estuary either is gradual, or marked by

a break in slope. The gradient of the platforms is related to their width. Wide platforms have nearly planar surface, while narrow platforms exhibit slopes up to 1:20. Sediments underlying the platforms consist of a thin veneer of mud grading via muddy sand into medium to fine quartz sand and finally limestone at depths of c 3.5 m. The wetland hydrology is maintained variably by estuarine water in some areas, or groundwater rise, or ponding by the mud veneers. The marginal platform wetland is inundated seasonally by estuarine water, and the water table falls to -50cm in the drier months. Marginal platforms are colonized by mixed low woodland comprising *M. raphiophylla*, *M. cuticularis*, *M. hamulosa* and *E. rudis* with an understorey of marsh plants and sedges of *Sarcocornia* spp, *Suaeda australis*, *J. kraussii*, and *Galinia trifida*.

9 Erosional sandy shore This shore type mainly occurs on the western side of Harvey estuary interspersed with the marginal platform shore type; the erosional sandy shore predominates around the nodes or more exposed stretches of the coast while the marginal platform type is located in the small scale indentations. The shore type also locally occurs along the shore of Peel Inlet and the modern exchange channel. The slope of erosional sandy shores most commonly ranges between 1:10 to 1:5, but may form a small cliff (<1 m). Shore erosion is evident both in the slope and the exposure of underlying stratigraphy. The sediments along this shore type usually are quartz sand of mixed grain size, with occasionally a thin layer of muddy sand exposed just below the surface. Erosion generally has incised into the hinterland such that woodlands of *Eucalyptus calophylla* border the shoreline, with an intermittent thin fringe of *J. kraussii*.

10 Limestone cliff—pocket beach shore This shore type is comprised of an eroding limestone shore alternating with small pocket beaches. The shore type occurs along the eastern side of Harvey estuary from Pt Grey southwards for c 7 km. Limestone forms cliffs and discontinuous littoral to sublittoral pavements around headlands and points, and steep sloped pocket beaches, less than 8 m wide, form along the intervening straight stretches. The pocket beaches are backed by relict beach ridges or Pleistocene dunes. Quartz sand is the dominant sediment of the pocket beaches. The vegetation on some limestone headlands consists of low closed forests of *C. obesa*, along the front of which is a narrow and often discontinuous fringe of *M. cuticularis* shrubs and *J. kraussii* sedge. The sedge fringe also colonizes the shore edge of the intervening beaches. Other limestone headlands are vegetated merely by the hinterland assemblages.

11 Lobate fluvial delta complex A wetland complex comprised of a lobate fluvial delta is situated along the NE shore of Peel Inlet, and is the combined delta system of the Serpentine and Murray rivers. Although the delta is a high-constructive type, wave reworking of the shore has resulted in the development of shore-parallel, low beachridges, separated by inter-ridge swales and flats. The deltaic lobe is 5 km wide at its apex. The Murray River is the dominant system for transporting sediment and constructing the delta. The present main channel of the Murray River is straight and flows along the central axis of the complex. The main channel divides into 7 distributaries, with associated mid-channel islands; one of the distributaries coincides with the Serpentine River distrib-

utary channels. There is a large deltaic plain adjoining the channels, and this can be divided into the following features: 1) abandoned channels, 2) levees, 3) lakes (= former, abandoned inter-distributary basins), 4) flats, 5) basins, 6) ridges and 7) hummock/swale system (= degraded levee system).

Inter-distributary flats and basins comprise most of the deltaic plain. They are small to medium scale wetland depressions separated by low-relief ridges which recurve and bifurcate. The depressions range in shape from narrow-linear to ovoid. There are now 3 abandoned channels, with associated levees, which are completely enclosed by the deltaic plain. However, flood water from these channels enters either the active channels or the estuary itself via basins and flats or drains. Ridges which occur on the deltaic plain are levee deposits, former spits and aeolian deposits; they are small scale and localized.

The stratigraphy of the delta is variable and complex, depending on formative environment, history and age of particular units. There are interlayered sheets, lenses and shoe-strings of various grain sizes of sand, muddy sand, sandy mud, mud, and at depth, coarse river gravel, and gravelly sand. Consequently, the hydrology of the system and its wetlands also is complex, depending on the stratigraphy, source of water, water dynamics, and distance from estuary shore.

The description of vegetation on the lobate delta is confined to the proximal end of the delta. The leptoscale channels of the deltaic plain are colonized by saltmarsh (mainly *Halosarcia* spp). The levees are colonized by *Halosarcia* spp. The ridges are colonized by *C. obesa* woodland with an understorey of open shrubland of *M. hamulosa* and open sedgeland of *J. kraussii* and *I. nodosa*. The depressions are colonized by saltmarsh (*Sarcocornia quinqueflora*, *H. halocnemoides* and *H. bidens*). The margin of the delta with the estuary is colonized by a mosaic of all of the above species.

12 Elongate fluvial delta complex An elongate fluvial delta (or birds foot delta), and an associated stranded deltaic plain, has been developed by the Harvey River. The normal components of such deltas are all present, ie distributary channels, levees, inter-distributary bays, subaerial plain and pro-delta slope. Consequently there are a wide range of wetland habitats within the deltaic complex. The modern, or active, delta is 2.5 km long, with a single, almost straight channel which divides into 4 distributary channels at the delta front. There also are several abandoned channels, also lined with subaerial levees. The inter-distributary basins range from sublittoral, to littoral, to seasonally inundated basins and flats. The older depressions in the deltaic plain are influenced by groundwater, while those at the front of the delta are influenced by estuarine flooding. The stranded deltaic plain has components of abandoned channels, levees, basins, and flats. The stratigraphy of the entire modern and stranded system consists of complex array of shoe-strings of sand and mud, interspersed with sheets of sand and mud, representing units formed in channels, in abandoned channels, levees and on floodplains.

The vegetation on this delta comprises assemblages of mixed low forests of *C. obesa*, *M. cuticularis* and *M. raphiophylla* on the levees; assemblages of scrub of *M.*

rhopiophylla, *M. hamulosa*, and *M. uncinata* on the abandoned levees; and assemblages of saltmarsh, dominantly of *Halosarcia* spp, on the flats and depressions.

Discussion

The results of this paper are discussed below in terms of variability of shore types, internal complexity of shore types and wetlands, the physical basis of the shore types and wetlands for developing vegetation habitats, and the peripheral vegetation response, and the research, education and conservation significance of the area.

It is apparent that a wide range of shore types and wetlands comprise the Peel-Harvey estuarine system, a factor that perhaps has not been fully appreciated by previous workers. Because of its large size, the estuarine system transcends several regional geomorphic units, and it could be anticipated that a variety of shore types would be developed. Overall, the range of macroscopic shore types are intimately linked to geographic location within the estuary (reflecting hydrodynamic setting), and to the type of hinterland backing the shore. For instance, the dynamics of the exchange channel environment has resulted in the development of modern tidal shoals and a tidal delta, and their stranded, relict equivalents. The discharge sites for the regional rivers have resulted in the development of deltas. Where the estuary shore is incised into the Spearwood Dunes, there are eroding limestone shores, eroding sandy shores, steep shores with fringing platforms, and locally, beachridge complexes and spit-lagoon systems. Shores fringing the terrain of Bassendean Dunes are beachridge complexes. Elsewhere, along the remainder of the estuary system, dependent on wind, fetch, and sand supply, beach ridge complexes are developed to varying extent and widths. Compounding this inherent variability due to regional factors is the effect of small scale processes that result in local variation in shore landforms and associated wetlands within any given area.

Within any given setting, the shore landforms and wetlands may be internally simple or complex. The marginal platforms and beachridges are simple systems, and spit-lagoon complexes and deltas are complex systems. The complexity of a shore landform and its associated wetlands is related to a variety of interacting features such as regional setting and aspect, local sedimentological processes, sealevel history, distance from and height above the estuary, and groundwater characteristics. This complexity also has not been fully appreciated by previous workers, and we consider it to be a critical feature to understanding the complexity of the types and distribution of the vegetation units that occur in this area.

Backshall & Bridgewater (1981) carried out a study of vegetation types, soil salinity and regional soil types, along the estuarine fringe, and produced a list of vegetation assemblages. Their study forms only the shoreward part of the shore-and-wetland study of this paper, and consequently their study accents the assemblages of the tidal marshes. This paper has tended to emphasize the full gradation of landforms and vegetation habitats from the estuarine shore through to the hinterland.

Vegetation variability, both in terms of floristic complexity of assemblages and their distribution [as laterally extensive formations, peripheral strips and fringes, or as

mosaics], is a direct response to habitat features, ie shore landform heterogeneity. Thus the description of the variable shore types and their associated wetlands provides a physical basis to understanding the development of habitats for vegetation. The internal heterogeneity of habitat types within a shore type or wetland result in a complex arrangement of vegetation formations within a given landform, or even subunit within a landform. However, it must also be emphasized that, given there is only a limited species pool of wetland vegetation in the region, within these vegetation formations the floristic composition can be relatively simple. The species recur through all wetland types but in variable structural formations, variable alliances, variable abundance and luxuriance. This variability can be determined by the physical factors of availability of water, consistency of water salinity, the lateral extent of uniform sedimentary substrates, height above the water table, shore slope, and protection from wind and waves.

The variability of shore types and wetland types along the extent of the estuarine shores, the internal heterogeneity of landforms and habitats within any given shore type, and the complex arrangement and distribution of vegetation in response to regional scale and local scale habitat differences highlight a need to preserve various tracts of shore for purposes of conservation, research and education. Clearly, the various delta types would need separate preservation. The transition from estuarine-influenced beachridges and wetlands through to hinterland freshwater-influenced beachridges illustrate a close relationship of landform, history and vegetation response that also need to be preserved at least for research and education purposes. Unique areas, such as the spit-lagoon complex in the NW Peel Inlet area and the elongate Harvey River delta, provide classic examples of vegetation and landform inter-relationships that are useful for research and education. Finally, areas of elevated (or stranded) deposits that were formed in the middle Holocene, eg the relict tidal delta, the stranded channel shoal complex, or the beachridges of the western Harvey Estuary Island Point area, provide valuable resources of information about sealevel history, Holocene climate history and long-term estuarine dynamics useful for research purposes.

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